Description

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Pulse Detonation Engine having an Aerodynamic Valve

This invention was made with United States Government support under Contract Number NAS8-98-035 awarded by the National Aeronautics and Space Administration. The Government has certain rights in this invention.

This application is a division of U. S. Patent Application Serial Number 10/026,236, filed Dec. 21, 2001 and incorporated herein by reference.

Technical Field

This invention relates generally to pulse detonation engines, and more particularly to the fluid dynamics of such engines. More particularly still, the invention relates to the valving of fluids employed in pulse detonation engines.

Background Art

Pulse detonation engines (PDE) represent an energy conversion device that has existed for some time, but which have recently received increased attention. Such engines generally combust fuel and an oxidant in a chamber, or combustor, to provide a component of thrust or force in an intended direction. The combustion occurs in the manner of discrete, i. e. pulsed, detonations. Tthe present invention is concerned with configurations that employ an open-ended chamber, such as a rocket nozzle, that may be employed for a component of thrust. A principal application for such engines is as a thrust source to propel an aerospace vehicle in the atmosphere or the vacuum of space. In such instance, the PDE is also a rocket engine.

The development of PDE's requires the ability to quickly fill an open-ended chamber with a detonatable mixture while purging the exiting exhaust gases with minimal mixing. For pulse detonation rocket engine applications where the open end of the chamber is likely to be exposed to a vacuum, the fresh charge of detonatable mixture must be contained in the chamber for several milliseconds before the detonation is initiated. Further, the mixture must be pressurized to levels on the order of 50-1000 psi with the chamber open to vacuum in order to generate thrust competitive with conventional rocket engines. Moreover, the process must be done at rates approaching or exceeding 100 Hz.

Two alternative concepts that may be used to control chamber pressure are mechanical valves and fixed throats, but each has significant limitations. The complexity and weight of a mechanical valve, combined with durability and sealing requirements in the hot exhaust flow, suggest that it would be difficult and/or impractical to implement in this application and environment. A fixed throat near the chamber exit would restrict the flow, allowing the chamber to be pressurized with high propellant flow rates while some propellant is lost through the exit. This arrangement suffers from the loss of efficiency due to propellant leakage during the fill process and from thrust reduction due to the reduced exit area of the throat.

A further discussion of the physics and operation of PDE's is contained in several U. S. Patents by T. R. Bussing, including U. S. 5,513, 489; 5,353,588; and 5,345,758. These patents discuss the use of a rotary valve, but only to control the admission of propellant and oxidant to each of multiple combustor chambers rather than to also control the pressure developed in the chamber. They rely upon an approach that uses multiple chambers each feeding into a common, restricted throat.

Accordingly, it is an object of the invention to provide an arrangement that is durable, relatively efficient, and simple, for controlling the pressure of fluids, such as propellants, in the chamber of a pulse detonation engine.

It is a further object to provide a pulse detonation engine in which the timing of detonation is optimized or tuned in accordance with the present invention.

It is a still further object to provide improved fluid injection mechanism for use with the pulse detonation engine in accordance with the invention.

Disclosure of Invention

A pulse detonation engine (PDE) is provided with an aerodynamic valve (aerovalve) for controlling the pressure of injected fluids, typically gases, but also including liquids, such as fuel or fuel and oxidizer, referred to as propellants, in an open-ended detonation chamber. The PDE includes a detonation chamber closed at a thrust wall end and open at the opposite, exhaust, end. A fluid injection mechanism injects pressurized propellant fluid into and directed toward the thrust wall end of, the detonation chamber. The propellant fluid is injected in a pulsed manner by the injection mechanism, and with sufficient pressure and velocity and such direction as to effectively restrict or prevent rearward flow of the injected fluid, thus forming a closed aerovalve. Moreover, the injected propellant fluid establishes a shock wave which, when moving rearward in the detonation chamber toward the exhaust end after reflection by the thrust wall end, serves in combination with the closed aerovalve to increase, or at least sufficiently conserve, the pressure of the fluid in the chamber, such that it is a pressure preferably greater than, or at least nearly as great as, that at which it entered. At the appropriate instant, the injected and

pressurized propellant is detonated, as by an ignition device, to rapidly combust the injected propellants. Because the exhaust end of the detonation chamber is not mechanically constricted, as by a mechanical valve, and the aerovalve is open because injection has ceased, the resulting combustion products readily exit to produce thrust. Such configuration avoids the concerns of a mechanical valve structure for controlling exhaust from the detonation chamber and does not require a mechanically-constricted throat structure which would otherwise impede exhaust flow.

The PDE is preferably tuned to optimize the specific impulse or thrust. This is accomplished by coupling the timing of the fluid propellant injection and the subsequent ignition to maximize performance. More specifically, the mass average chamber temperature and pressure are at a maximum as the reflected shock wave nears the injection mechanism. The ignition is timed and positioned such that the resulting detonation wave, which moves at a velocity greater than the reflected shock wave, arrives at the injection mechanism at the same instant as the reflected shock wave.

The propellant injection mechanism is a high frequency pulse valve which delivers and injects pressurized pulses of propellant, typically fuel and oxidizer, to the detonation chamber of the PDE. Various arrangements may be used for providing such pressurized pulses of propellant. However, in the propellant injection mechanism of the preferred embodiment, each propellant component is supplied, at pressure, to a respective slotted disk type of valve. The slotted disk valve includes at least one rotating disk having a plurality of slots, and a complementary slotted disk, typically stationary, such that the slots of the two disks port (open) and unport (close) in rapid succession. The propellant pulses are delivered from the disk valves

to the detonation chamber via injection ducts which are positioned and directed to provide the aerovalve of the invention.

One embodiment of the propellant injection mechanism comprises one or more injection valves offset from the axis of the detonation chamber and in which the rotating disk is driven by a spring-biased drive member at the axis of the disk, but offset from the detonation chamber axis.

Another embodiment of the propellant injection mechanism comprises a pair of annular injection valves that encircle the detonation chamber and in which annular fixed and rotating slotted disks are disposed coaxially with the detonation chamber to provide the pulsed injections.

The foregoing features and advantages of the present invention will become more apparent in light of the following detailed description of exemplary embodiments thereof as illustrated in the accompanying drawings.

Brief Description of Drawings

Fig. **1** is a simplified, cross-sectional view of a pulse detonation engine (PDE) employing an aerodynamic valve (aerovalve) in accordance with the invention;

Figs. **2A**, **2B** and **2C** are simplified diagrammatical depictions of the PDE of Fig. **1** showing, respectively, initial injection of propellant fluid to establish and close an aerovalve and also create a shock wave, detonation of propellant fluid at appropriate timing of the reflected shock wave, and final exhaust and venting of combusted propellant fluid through relaxed, or opened, aerovalve;

Fig. **3** is a graphical depiction of the filtered and normalized pressure histories at various locations in the PDE during a representative cycle of pulse operation, but omitting actual detonation;

Fig. **4** is a graphical depiction of the chamber pressure, temperature and leakage during a representative cycle of pulse operation, but omitting actual detonation;

Fig. **5** is a graphical depiction of a single pulse pressure trace from multiple repetitive detonations;

Fig. **6** is a graphical plot of the aerovalve performance metrics of pressure and leakage as a function of the injection angle (β) of the propellant fluid;

Fig. **7** is a simplified diagrammatical depiction of a PDE in accordance with the invention, illustrating multiple axially-spaced stations for the injection of propellant fluid;

Fig. **8** is a sectional view of one embodiment of a slotted-disk pulse valve for metering and injecting propellant fluid to the PDE chamber to provide the aerovalve in accordance with the invention;

Figs. **9A** and **9B** depict, respectively, the rotating disk and the stationary disk of the pulse valve of Fig. **8**;

Fig. **10** is a simplified sectional view of a second embodiment of a pair of slotted-disk pulse valves for metering and injecting propellant and oxidant fluids to the PDE chamber to provide the aerovalve in accordance with the invention; and

Fig. **11** is an exploded view of the major elements of the slotted-disk pulse valve assembly of Fig. 10.

Best Mode for Carrying out the Invention

Referring to Figs. **1** and **2A-2C**, there is illustrated in Fig. **1** a simplified, somewhat diagrammatic, cross-sectional view of a pulse detonation engine (PDE) **10** employing fluid injection mechanism **12** to provide the aerodynamic valve (aerovalve) **14** depicted diagrammatically through the use of gas flow arrows in Figs.**2A-2C** in accordance with the invention. The PDE **10**

is typically an elongate tubular structure **11** having a closed thrust wall end **16** and an opposite exit, or exhaust, end **18** that is open. A fluid injection mechanism **12** is located intermediate the opposite ends **16** and **18**, relatively toward the exhaust end **18**, and may typically include an annular injector member **20** and associated fluid pulse injection valves **22** and **24**. The annular injector member **20** may conveniently be included as a structural portion of the tubular PDE structure. The region of the PDE between the injector member **20** and the thrust wall end **16** comprises the detonation, or combustion, chamber **26**. An active ignition source, such as spark plug **28**, is located in a wall of the PDE in communication with the detonation chamber **26**.

The PDE **10** is provided with a supply of fuel, such as hydrogen gas or liquid, via the fluid pulse injection valve **24**, and with a supply of oxidizer, such as oxygen gas or liquid, via the fluid pulse injection valve **22**. The fuel and the oxidizer, in liquid or gas phase, are injected into the detonation chamber **26** via fuel injection ducts **30** and oxidizer injection ducts **32**, respectively, in the annular injector member **20**. The inner ends of the ducts **30** and **32** define respective fuel injection ports **30′** and oxidizer injection ports **32′** at their interface with the detonation chamber **26**. The fuel injection ducts **30** and the oxidizer injection ducts **32** are oriented such that, at least at their respective ports **30′** and **32′**, they form an angle β with the axis, or centerline, of the detonation chamber **26** and the tubular structure **11** of the PDE **10**. This orientation is selected so as to inject the fuel and oxidizer relatively forward toward the thrust wall end **16** of the PDE **10**. In this way, the advantages of the aerovalve **14** of the invention are obtained, as will be explained in greater detail.

Although the fuel injection ducts **30** and the fuel injection ports **30'** are depicted in Fig. **1** as being displaced longitudinally slightly from the oxidant injection ducts **32** and the oxidant injection ports **32'** for convenience of illustration, it will be appreciated that they may also be at substantially the same longitudinal position, as will become evident later herein. In that latter instance, they may collectively appear as a single, nominally continuous, annular entry port.

Referring to the diagrammatical illustrations of Figs. **2A-2C**, there is depicted a cycle of operation of the PDE **10**, including the associated aerovalve **14**. Fig. **2A** shows the fuel and oxidizer propellants being injected into the detonation chamber **26** under high pressure and speed via ducts **30** and **32** respectively. Assuming the PDE **10** is operating at high altitude or in space, the initial pressure in the detonation chamber **26** may be at a near-vacuum condition. The propellant flow expands as it is injected toward the thrust wall end **16**. A shock wave **34** is formed at the leading edge of the advancing propellant flow. Importantly also, the high velocity of the flow toward the thrust wall end **16** limits its ability to turn toward the exhaust end **18** and leakage, represented by arrows **36**, is thereby minimized or prevented. This latter characteristic results in the formation and relative closing of an aerodynamic valve, identified by the independent reference numeral **14**, and thus aids in containing and compressing the injected propellants. Referring to Figs. **2A** and **2B**, when the supersonic flow of the shock wave **34** contacts the thrust wall end **16**, it is reflected back through the detonation chamber **26** toward the injection region and the exhaust end **18**. This reflected shock wave **34** travels back over the injected propellant gas, both stagnating and heating the gas, as

well as recovering pressure. The resulting pressure in detonation chamber **26** is seen to increase significantly, as will later be illustrated graphically. At the appropriate instant, the compressed and heated propellant gas is detonated, as by the firing of the spark plug **28** represented in Fig. **2B**. The resulting detonation also produces a detonation wave front (not separately shown) which advances in all directions from its source at a velocity greater than the reflected shock wave **34**. The timing of ignition and resulting detonation are preferably selected such that the reflected shock wave **34** and the detonation wave front arrive at the region of the injector ducts **30** and **32** at substantially the same time, at which time the mass average pressure and temperature in detonation chamber **26** are a maximum.

Referring to Fig. **2C**, the PDE **10** is illustrated shortly after the detonation of Fig. **2B** has occurred. It will be noted that because there is no further injection of fuel and oxidant, the aerovalve **14** has relatively opened or relaxed, to permit the rapid and thorough egress of the combusted propellants and the associated development of the desired thrust impulse. Following the opening of the aerovalve **14** and the exhaust of the combusted propellants, the PDE **10** is ready to begin a new pulse cycle by receiving a new injection of propellant, as depicted in Fig. **2A**. In the interest of maximizing the cycle-average thrust, it is desirable to both fill, and later exhaust, the detonation chamber **26** as rapidly as possible. Cycle rates of 100 Hz are typical, resulting in cycle times of about 10 ms. It should be noted that cycle rates vary inversely as a function of the length of the detonation chamber **26** and thus, may be controlled and varied to some extent by the selection of the length of the detonation chamber **26**. A further understanding of the invention is obtained with reference to the graphical

depictions of Figs. **3** and **4**, which represent data obtained from an instrumented PDE **10** during a cycle of operation, but without ignition or detonation. The pulse detonation chamber **26** was cylindrical, having a diameter of about 4 inches and a length of about 40 inches, with the injection mechanism **12**, and particularly the injection ducts **30** and **32**, being located at the aft end of the detonation chamber, just forward of the exhaust end **18** of the PDE **10**. The operating environment at the exhaust end **18** of PDE **10** was at a pressure less than 1 psia.

Referring to Fig. **3**, the normalized value of pressure, p/Pt_{inject}, for each of several locations at, or in, the PDE **10**, is plotted as a function of Time (in milliseconds). In the expression for the normalized value of pressure, p is static pressure and Pt_{inject} represents the injected total pressure. It will be seen that, as would be expected, the injection pressure, Pt_{inject}, at the injection ports **30'** and **32'** is substantially at unity. However, the pressure within the detonation chamber **26** is seen to experience a rapid increase from near zero to a maximum that is, in accordance with the invention, greater than the injected pressure, in this instance about 1.15, or 15% greater. The lowermost trace is representative of the ambient pressure at or near the exhaust end **18** of the PDE **10**, and is indicative of a low, near-vacuum pressure except immediately following exhaust of the injected propellants. The remaining trace is that of Pt_{leak}, which is commensurate with the pressure of the leakage flow from the aerovalve **14**, represented by the leakage arrows **36** of Figs. **2A-2c**.

Referring to Fig. **4**, the pressure, temperature, and leakage in detonation chamber **26** are displayed in a normalized form for one fill and exhaust cycle. The time base τ is normalized time, and represents ta/l_t, where "t"

is time, "a" is the speed of sound and "l_c" is the length of detonation chamber **26** as measured between the injection ports **30'/32'** and the thrust end wall **16**. The values along the ordinate are normalized and dimensionless. The normalized value of the pressure of the injected propellant(s) is seen to increase until about τ= 2.75, at which time it is about 1.2. or 20% greater than the injected pressure, Pt_{inject}, which in turn is typically about 50 times greater than the ambient pressure. Similarly, the temperature in the chamber **26** increases until about τ=2.75, at which time it is about 1.3, or 30% greater than the temperature at the moment of initial injection. At, or shortly before, τ=2.75, detonation would normally occur, however detonation is omitted in this example and the pressure is seen to drop rapidly, with the temperature also dropping at a lesser rate. Further, the leakage of fluids, initially undetonated injectant, is seen to be relatively low until about τ=2.75, being only about 0.15, or 15%. Thereafter, the leakage of previously injected gases increases rapidly because further injection has terminated and the aerovalve **14** relaxes, or opens. Had detonation occurred, the combusted gases would rapidly exit the detonation chamber **26** as they produce thrust. In the foregoing example, the fuel and oxidant were injected at an angle, β, of 30^0.

Referring to Fig. **5**, there is provided a graphical depiction of a single pulse pressure trace from a 25 Hz run with repetitive detonations. The initiation of fuel injection is seen at the left side origin of the trace and the normalized pressure remains relatively constant for a little longer than 1 ms as the shock wave **34** travels toward the thrust wall end **16**. Then, at T= 1.29 on the graph scale, the shock wave is reflected and the pressure in the detonation chamber **26** rapidly and

significantly increases until, at about T= 1.294, detonation occurs and the pressure increases very rapidly and very significantly. Shortly thereafter, the combustion products exhaust and produce the desired thrust, as indicated by the rapid decline in pressure between the detonation and initiation of the next injection of propellant about 2 ms later.

Referring to Fig. **6**, the aerovalve performance metrics of pressure and leakage are displayed as a function of the injection angle β of the propellant fluid. The ordinate represents normalized values for the performance of aerovalve **14** for the various injection angles β measured along the abscissa. The maximum normalized mass-average total pressure per fill cycle is Max Pt^m/Pt_{inject}, where Pt^m is the chamber mass-average total pressure and Pt_{inject} is the injected total pressure. This parameter is important because the total impulse imparted to the system during a detonation blowdown is directly proportional to the post-detonation mass-average total pressure; the higher the fill pressure, the higher the post-detonation pressure. It will be noted that the normalized mass-average total pressure is greatest when the injection angle β is smallest, as when β is 0^0. In that instance, the propellant would be directed parallel to the axis of detonation chamber **26** in the direction of the thrust wall end **16**, and the maximum could theoretically be 60% greater than the injected pressure. Conversely, if the propellant is injected at an angle β of 90^0 to the chamber's axis, there is essentially no increase in the pressure over the injected pressure. This analysis indicates the desirability of making the injection angle β as small as possible in order to maximize the pressure increase. It will be appreciated, however, that the mechanics of injecting propellant at an angle of 0^0 may be difficult or impractical in an operating configuration, and angles in the range of about

20^0 to 45^0 are practicably obtainable and are seen to provide significant pressure increases, as for instance 50% and 25%, respectively. Further, the leakage parameter M_{leak}/M_{inject} is a ratio of the mass of propellant gas leaked to the mass injected during fill. It will be seen that such leakage is less for a small injection angle β, and is significantly greater as the angle increases toward 90^0. It is thus again desirable to keep the injection angle β as small as practicably possible. In the foregoing analysis, the pressure of the injected propellant, Pt_{inject}, is 50 times greater than the ambient pressure, and the ratio of the area of the injector ports **30'/32'** is the same as the cross-sectional area of the detonation chamber **26.**

A further variable that may be introduced to affect performance of the PDE is the addition of a second propellant injector, or a second set of propellant injectors, as part of the fluid injection mechanism **12'** (shown in broken line), at a location intermediate the initial injector, or injector set, **30/32**, and the thrust wall end **16**. In the embodiment depicted in a simplified diagrammatic form in Fig. **7**, the initial injector ducts **30/32**, depicted for simplicity as a single duct, are at, or near, one end of detonation chamber **26** of a PDE **110** and the thrust wall end **16** is at the opposite end. The second set of injectors is represented by injector ducts **130/132** and respective ports **130'/132'**, which are located approximately midway between the initial injector ducts **30/32** and the thrust wall end **16**. Such arrangement provides for the injection of propellants from the two locations at substantially the same time, which has been seen to result in a substantially faster filling rate and with substantially less leakage by the aerovalve **14.** Under similar conditions and differing only in the number of injector sets, the single injector set configuration

was seen to have a relative leakage value of 0.14 and fill time value of 2.94, whereas those same values for the two injector set configuration are 0.10 and 1.51, respectively. The advantages of including a second injector set are tempered by added complexity and slightly decreased pressure and temperature values, the latter believed being due to interference between the reflected shock wave from the added injector set and the advancing shock wave from the initial injector set. Also, as mentioned previously, some further advantage is derived if the injection angle β is kept relatively small, as for instance 45^0 or less, and preferably about 30^0.

Attention is now given to a detailed consideration of one embodiment of a representative propellant injection valve, such as the fluid pulse injection valve (PIV) **24** for injecting fuel, such as hydrogen liquid or gas. Referring to Figs. **8**, **9A** and **9B**, there is illustrated a slotted-disk pulse injection valve **24**, including the fixed disk **40** and rotating disk **42** which form parts thereof. The PIV **24** is designed to start and stop the flow of fluids, such as liquids or particularly gases, at high frequencies, without the shortcomings of prior devices that were frequency limited. The PIV **24** employs two circular disks, one being a fixed disk **40** and the other being a rotating disk **42**. The faces of the disks **40** and **42** are ground to precision flatness and surface finish. The disks **40** and **42**, respectively, have radial slots **44** and **46**, respectively, cut into their faces such that when they are in facing mated engagement and rotated on a concentric axis, the slots **44** and **46** port (open) and unport (close). The frequency of the porting and unporting action is a function of the number of radial slots **44/46** in the faces of disks **40** and **42** and the relative rotational speed of those disks. Because the

number of slots **44/46** can be relatively large, i. e., 10 to 20, high frequency operation can be achieved at relatively low rotational speeds. The angular extent of the slots **44/46** is typically constant from the radially innermost to the radially outermost portion of a respective slot, though the angular extent of the slots **44** may differ somewhat from that of slots **36.** In either event, the angular extents are typically less than about 5^0-10^0 and there may be, for example, 10 to 20 such slots per disk. In the instance of 20 slots, a frequency of 100 Hz is obtained at a rotational speed of 300 rpm. The faying surfaces between the rotating disk **42** and the stationary disk **40** are coated with a dry film lubricant compatible with the fluid being injected, to facilitate relative motion and sealing. Depending on the relative positioning of the disks **40** and **42**, that face of the disk closest to the ducts **30/32** and the detonation chamber **26** (seen in Fig. **1**) may be protected with a thermal barrier coating to minimize distortion from thermal gradients and transients. Further protection may be obtained by recessing the valve from the detonation flow path, as by ducts **30/32** and/or supplying a bleed fluid such as air, if available, over the sensitive surface.

Referring to the PIV **24** in greater detail, a housing **50** provides structural support for the PIV assembly, and includes mounting flanges **51** for mounting it in fixed relation to the structure **11** of the PDE **10.** The housing **50** includes a generally cylindrical through-bore and coaxial counter bores. An electric motor **52** or similar actuator for providing rotary motion, is mounted to the outboard end of the PIV housing **50**, and a rotary drive shaft **54** is connected thereto by a suitable coupling **56** for transmitting rotary torque and motion from the motor **52** to the drive shaft **54.** The drive shaft **54** extends forwardly into the bore in housing **50** in

radially-spaced relation, and is centered and rotatably supported therein by bearings **58**. The bearings **58** are axially spaced from one another by spacer **60**, and are retained at their ends against axial movement by snap rings **62** seated in the housing **50**, and possibly additional snap rings in the shaft **54**. The outside diameter of the drive shaft **54** is increased in a step at its inboard end to create a shoulder portion **64** against which the forward bearing **58** may axially bear and against which the inner diameter of a seal **66** may radially bear. The drive shaft **54** contains an axially-extending, blind, hexagonally-shaped (hex) recess **68** formed, as by machining, in its forward, or inboard, end for receiving a ball hex driver **70** in axially-sliding relationship therein. The shank of ball hex driver **70** is formed in a complementary hex shape with the recess **68** in the drive shaft **54** to prevent relative rotation there between. Of course other complementary geometries containing flats to prevent rotation would also suffice. The ball hex driver **70** has a ball hex driver head **71** formed at its forward, distal or inboard, end for driving engagement with the rotating disk **42** via a hex shaped recess **71'** centered in the disk **42**. A compression spring **72** is seated in the recess **68** in drive shaft **54**, and acts against the rearward, proximal or outboard, end of the ball hex driver **70** to urge it forward and into engagement with the rotating disk **42**, as will be described.

The forward, or inboard, end of the PIV housing **50** includes a relatively large counterbored region forming a plenum **74**. A fitting **76** on housing **50** serves to admit propellant, in this instance fuel, to the plenum **74** via a conduit **78** in the housing. The rearward end of the plenum is closed by the seal **66**, which extends radially from the shoulder **64** on drive shaft **54** to the radially inner wall

of housing **50**. The disks **40** and **42** are mounted in the forward end of PIV housing **50** such that they define the forward end of the plenum **74**. The fixed disk **40** is axially forwardmost in housing **50**, and is statically mounted therein in a sealed manner that prevents motion relative to the housing, axially, circumferentially, and radially, as by weld, braze, thread, or the like, or by machining. The faying surface of fixed disk faces rearwardly. The rotating disk **42** is positioned immediately rearward of the fixed disk **40**, with the former's faying surface facing forward in opposition to that of the latter. The rotating disk **42** is free to rotate when driven by the ball hex driver **70**. The ball hex driver head **71** is urged forward by compression spring **72**, into mated driving engagement with the rotating disk **42** in, and via, the hex shaped recess **71'** in the disk. This coupling and driving arrangement compensates for fore and aft angular misalignment (wobble) between fixed disk **40** and rotating disk **42** by allowing the faying surfaces of the disks to float with limited axial and wobble displacement and thereby maintain intimate contact during rotation. In addition to the nominal preload that the compression spring **72** provides, the propellant pressure in the plenum **74** applies a force load to the rotating disk **42** to maintain sealing contact between it and the fixed disk **40**. The forward end of plenum **74** is sequentially opened and closed by means of the slots **44** and **46** in disks **40** and **42**, respectively, thus successively porting and unporting. In this way, propellent admitted to the plenum **74** under pressure is discharged (injected) to the detonation chamber **26** as discrete, high frequency, pressurized pulses for providing the benefits attainable with such operation.

Referring now to Figs. **10** and **11**, there is depicted a second embodiment of a fluid injection mechanism **112**

comprising a pair of annular injection valves **122** and **124** that serve to inject pulses of the oxidant and the fuel, respectively. Unlike the injection valve arrangement 24 of Fig. **8** wherein the axis(es) of the fixed disk(s) **40** and the rotating disk(s) **42** are offset from the axis of the detonation chamber **26** of the PDE **10**, the present fluid injection mechanism **112** provides a ganged pair of annular injection valves **122** and **124** having fixed annular disks **240** and **140** respectively, and rotating annular disks **242** and **142** respectively, all of which are concentric and coaxial with the axis of detonation chamber **26**. The fixed disks **240** and **140** have radial slots **244** and **144** respectively, and the rotating disks **242** and **142** have radial slots **246** and **146**, respectively. The injection valves **122** and **124** are axially spaced by a common annular injector member **120** that is positioned therebetween adjacent to the respective rotating disks **242** and **142**. The annular injector member **120** has a lobed mixing tang **190** that defines, in cooperation with the rotating disks **142** and **242** and their slots **146** and **246**, the fuel injection ducts **130** and the oxidant injection ducts **132** that extend radially inward and axially forward from the disks at the desired injection angle, β. The annular injector member **120**, and the rotating disks **142** and **242** are all mounted for rotation coaxially about the detonation chamber **26**, with at least part the injector member **120** defining an annular portion of the wall of the detonation chamber. The rotating disks **142** and **242** are connected to the annular injector member **120**, as by a key, pin, or spline-type coupling arrangement **192** that allows limited relative axial motion but prevents relative circumferential motion, such that the three elements rotate in unison but some limited axial angular or "wobble" motion therebetween is permitted to allow

each rotating disk to "float" relative to its associated fixed disk.

The fixed disks **240** and **140** are each further mated with fixed, plenum-forming members **240′** and **140′**, respectively, to define plenums **274** and **174**, respectively, and include fluid inlet passages **278** and **178**, respectively, for supplying the oxidant and fuel. As with the Fig. **8**, **9a**, and **9B** embodiment, the faying surfaces of the fixed and the rotating disks are in sliding contact with one another and thus, are machined and processed to a fine finish and receive lubricants, such as a dry film and grease, to facilitate operation. To assure that the flat mating faying surfaces of the rotating and fixed disks come together and mate without any angular mismatch in the axial direction to insure good running and sealing, the rotating disks **142** and **242** are permitted to float a small amount relative to the respective fixed disks **140** and **240**. More specifically, as noted above, the coupling arrangement **192** allows the rotating disks **142** and **242** to move axially angularly, or "wobble", relative to the annular injector member **120** that is positioned therebetween. A number of compression springs **172** are interposed and arranged circumferentially, under preload, between the injector member **120** and the outer rims of the respective rotating disks to resiliently bias the rotating disks **142** and **242** into close mating and sealing contact with the respective faying surfaces of the fixed disks **140** and **240**.

In operation, the annular injector member **120** and the associated rotating disks **142** and **242** are rotated, as by a motor driven friction belt **194** or geared drive (not shown) engaging the injector member **120**, and the slots **144**, **244** **146** and **246** port and unport as earlier described. Assuming about 20 slots on the disks, pulses of fuel and oxidant are provided at 100 Hz when the

rotating portion of the fluid injection mechanism **112** is driven at 300 rpm.

Although the invention has been described and illustrated with respect to the exemplary embodiments thereof, it should be understood by those skilled in the art that the foregoing and various other changes, omissions and additions may be made without departing from the spirit and scope of the invention. For instance, the fluid propellants injected may each be in either the liquid or gaseous phase; the pressure of the propellants in the detonation chamber at the moment of detonation may be less than, but nearly as great as, the pressure of the propellant as injected; the fluid injection mechanism for the pulse detonation engine may employ suitable fluid pulse injection arrangements other than the slotted disks of the preferred embodiment; and the use of PDE's is not limited to aeronautical and space applications, but may be used for power generation in other applications, including land-based machinery, either linear or rotary.